Multi Resolution Touch Panel with Built-in Fingerprint Sensing Support

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***Abstract*—In today's technology driven world, it is essential to build secure systems with low faulty behavior. Authentication is one of the primary means to gain access to secure systems. Users need to be authenticated in order to gain access to the services and sensitive information contained within the system. Due to the surge in the number of touch based smart devices, there arises a need for a compatible authentication system. Historically, fingerprints have served in its fullest capacity to establish the uniqueness of an individual's identity. It can be detected using capacitive sensing techniques. In this paper we present a novel unified device using transparent electronics for both fingerprint scan and multi-touch interaction. We discuss a high resolution transparent touch sensitive device and a read out circuit that drives the capacitive sensor array for touch interactions at low resolutions and for fingerprint sensing at higher resolutions. Using circuit simulation and custom Verilog-A model for transparent thin-film transistors, we verified that our design can sense fingerprints in 8.25 ms and detect touches in 0.6ms with an efficient power consumption of 1 mW. The results show that such a device can be realized and can serve as a very efficient means of user authentication. Furthermore, from the usability aspect, the proposed device is essential as it provides user transparent and non intrusive authentication.**

I. INTRODUCTION

The recent improvements in the technology for developing electronic material have led to the implementation of Transparent Thin Film Transistors(TTFTs) (*e.g.*, [9], [12]). In comparison with silicon based electronics, TTFTs enable the manufacturers to design and build a variety of transparent electronic components to meet the emerging requirements of optoelectronic devices. In the past, most of the research on transparent electronic applications have been focused on displays. In this paper we discuss one such emerging application of transparent electronics that leverages the high performance transparent semiconductors and aims to satisfy the growing need for easy to mobile identity management in a rapidly expanding market.

There has been a rapid growth in the use of smart, touch based mobile devices (*e.g.*, smartphones, tablets) which are quickly replacing personal computers, both in numbers and net usage. According to the market analysis and predictions, in 2015, there will be 1.5 billion smartphones in use worldwide The wide adoption of smartphones creates a strong demands for phone based user identity detection that can enhance user security, enable us to design user friendly access control and carry out smoother and safer online activities (*e.g.* password free access for web sites from a phone). Many approaches have been proposed for smartphone based user identity management by utilizing the smartphone sensors such as camera for user identity recognition. Vendors have also integrated stand-alone optical fingerprint sensing systems with some of the smartphone models (e.g., Motorola Atrix 4G and Apple's iPhone 5S).

In this paper we explore a revolutionary approach. This approach takes advantage of the fact that both touch interactions and fingerprint scan involve the finger coming in contact with the screen. A novel user identity sensing approach can be designed to identify the user from fingerprint data sensed during the user's interactions with the screen. Although it is currently considered as two distinct areas of application, both fingerprint scan and touch detection can be achieved through capacitive sensing. The current devices have a stand-alone touchscreen while our approach aims to integrate fingerprint scan capability along with the traditional touchscreen. The continued improvement of transparent electronic techniques and fabrication process enables us to create a unified capacitive sensing panel which can support both fingerprint scan and touch detection.

Such an approach provides innumerable and unmatched applications for touch based consumer electronics. The device supports both touch interactions and identity management within a single unit. It has many advantages over competing user identity detection and sensing techniques. Firstly, it provides stronger and more reliable identity detection performance because fingerprint recognition is historically well established, reliable and highly accurate method for identity verification. Secondly, it is transparent to the mobile user and non-intrusive. Thirdly, it incurs neither physical (*e.g.*, extra steps/actions that a user has to take) nor cognitive burden (*e.g.*, remembering a password) on the mobile user, making it more user friendly and responsive than other competing approaches.

The main contributions of our work include:

- Design of a novel system that unifies touch detection and fingerprint scan with a single capacitive sensing based system using transparent oxide semiconductors;
- Development of the tools and models for simulating and modeling this unified system that leverages advancements in the transparent thin-film transistors;
- Proposal of a novel solution such as multi-resolution readout circuit for the unified system that supports dual operation modes to use the device as a touch panel and/or fingerprint scanner based on the context; and
- Demonstration of potential usage of the proposed system for integrating it with touch based mobile devices.

II. DESIGN AND MODELING

The objectives of our study are to explore, model and simulate a unified capacitive sensing based touch-fingerprint device using state of the art technologies in transparent oxide semiconductors and design tools.

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TABLE I
SIMULATION MODEL PARAMETERS FOR TFT DEFINITION

Geometric Model Parameters	Symbol	Units
Channel Width	W	Meters
Channel Length	L	Meters
Gate-Source/Drain Overlap	$GSD_{OVERLAP}$	Meters
Channel-Source/Drain Overlap	$CSD_{OVERLAP}$	Meters
Gate Insulator Thickness	t_{OX}	Meters
Channel Thickness	t_{ch}	Meters
Physical Model Parameters	**Symbol**	**Units**
Turn-On Voltage	V_{ON}	Volts
Relative Dielectric Constant	K_{OX}	Volts
Mobility Polynomial Coefficient	C_0 to C_6	Volts
Channel Resistivity	$\rho_{CHANNEL}$	$\Omega \cdot cm$
Contact Resistivity	$\rho_{CONTACT}$	$\Omega \cdot cm$

A. TTFT Device Modeling

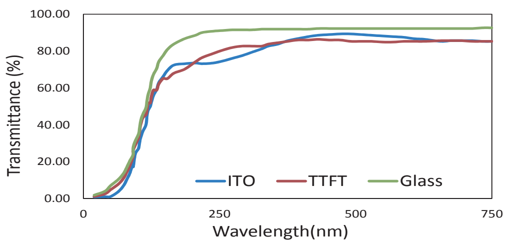


Fig. 1. Measured transmittance of a fabricated transparent amorphous oxide TFT, glass substrate [1].

High performance transparent thin-film transistors (TTFT)fabricated at room-temperature using transparent amorphous oxide materials such as SnO_2, ZnO, In-Ga-Zn-O (*e.g.*, [1], [6], [8], [9]). The mobility is between 10 and 50 $cm^2 s^{-1} v^{-1}$ as reported in various studies. Figure 1 compares the transparency level of glass, ITO (Indium tin oxide), and TTFT. ITO is one of the most widely used transparent conducting oxides known for its electrical conductivity and optical transparency. Typically, for TTFT, ITO is employed as the gate, source and drain electrode. Capacitive touch panel often consists of two parallel transparent ITO film layers that are separated from a sensor glass layer. A capacitive touch panel can be created using only ITO and glass. For only sensing touches, thin-film transistors are not necessary. However, for scanning fingerprint based on the principle of capacitance sensing, thin-film transistors are needed. Such fingerprint scanner is often called TFT capacitive fingerprint reader. Our idea is to create a unified touch-fingerprint sensing device that can support both touch detection and fingerprint imaging using TTFT and transparent conductive material such as ITO.

Modeling and simulation play important roles in designing integrated circuit systems before fabrication. For simulating our capacitive touch-fingerprint sensing system, a device model for transparent TFT is needed. For such a purpose, we use Hoffman's closed form mobility approach to model transparent amorphous oxide TFTs [5]. The approach uses high-order polynomial expressions to define TFT I-V characteristics. In [11], the author applies and validates the Hoffman's closed form approach for modeling amorphous oxide TFTs. The model includes all modes of operation (pre-saturation, saturation).

Equation defining the drain-source currentI_{ds} is described below(equation 2),

$$\mu_{AVE}(V_{EFF}) = \begin{cases} 0, & \text{if } V_{EFF} \le 0 \\ \sum_{i=0}^{n} c_i [V_{EFF}]^i, & \text{if } V_{EFF} > 0 \end{cases} \quad (1)$$

$$I_{ds} = \begin{cases} 0, & \text{if } V_{GS} \le V_{ON} \\ C_{INS}\frac{W}{L}\sum_{i=0}^{n}(\frac{c_i}{i+2}[(V_{GS}-V_{ON})^{i+2} - (V_{GS}-V_{ON}-V_{DS})^{i+2}]), & \text{if } V_{DS} \le (V_{GS}-V_{ON}) \\ C_{INS}\frac{W}{L}\sum_{i=0}^{n}(\frac{c_i}{i+2}[(V_{GS}-V_{ON})^{i+2}]), & \text{if } V_{DS} > (V_{GS}-V_{ON}) \end{cases} \quad (2)$$

Where W is the width of the channel, L is the length of the channel, V_{on} is the turn-on voltage(V),V_{gs} is the gate-source voltage(V),V_{ds} is the drain-source voltage(V) and μ_{AVE} is average mobility(1). C_{ins} is gate capacitance density defined by the equation $C_{ins} = \frac{\epsilon_0 K_{OX}}{t_{OX}}$ [11] where ϵ_0 is the permittivity of free space, K_{OX} is the relative dielectric constant and t_{OX} is the gate insulator thickness. c_i is the mobility polynomial coefficient where i indicates the order of the polynomial. μ_{AVE} is the dependant variable of the device model structure which can be expressed as,

$$\mu_{AVE}(V_{EFF} : c_0, c_1, c_2, c_3, c_4, c_5, c_6) \quad (3)$$

where V_{EFF} is the dependant variable and $c_0, c_1, c_2, c_3, c_4, c_5, c_6$ are model parameters.

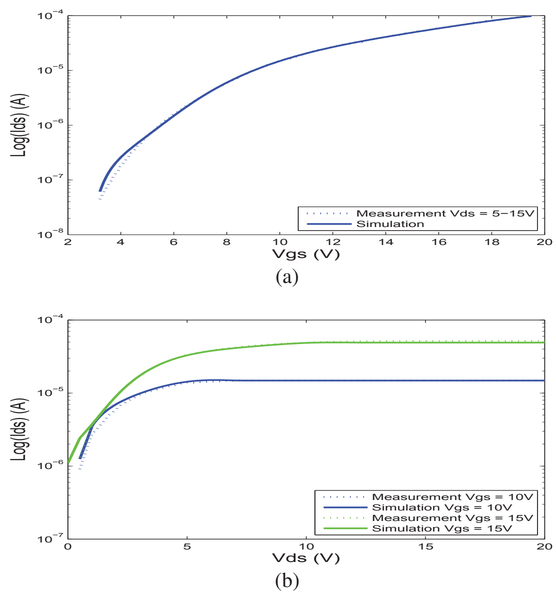


Fig. 2. Modeling of electronic properties of SnO_2-TTFT in Verilog-A, where (a) illustrates simulated and measured DC transfer characteristic (log[Id]-Vgs) of SnO2-TTFT; and (b) illustrates simulated and measured DC transfer characteristics (log[Id]-Vds) of SnO_2-TTFT. Measured DC data is based on fabricated SnO_2-TTFT device [1]. The TFT modeling approach is based on [5] and [11]. For many data points, the simulation and measurement results are closely matched and overlaped.

We implement the TTFT model in Verilog-A because it provides a mean of modeling devices at a wide range of levels of abstraction and at the same time integrates the implemented model with computer aided design tools. Simulation of the designed unified touch-fingerprint sensing system was conducted using SmartSpice and TFT CAD tools from Silvaco. Figure 2 compares the output characteristics of our Verilog-A TTFT module with measured data from fabricated transparent amorphous oxide TFT [1]. As illustrated by the results, the simulated device characteristics are very close to the experimental data, which indicates that our model is valid

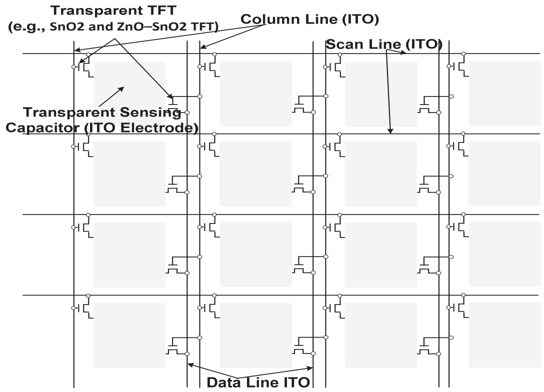


Fig. 3. Circuit model of capacitive sensing array using transparent oxide semiconductors. All components are made from transparent materials (*e.g.*, ITO, transparent TFT) and glass substrate.

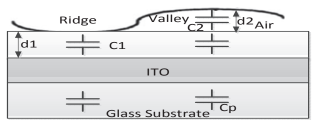


Fig. 4. Principle of capacitive fingerprint sensing.

for circuit simulation and modeling purpose. The simulated DC transfer characteristic between Id-Vds under 10V Vgs is on average 94.26% accurate when compared with the measured result. Under 15V Vgs, the simulated DC transfer characteristic between Id-Vds is on average 97.09% accurate.

a) Unified Capacitive Sensing: Figure 3 shows an abstract circuit model of transparent TFT based touch-fingerprint sensing array. All the components are made from transparent materials (ITO, glass, TTFT). The array works on the principle of capacitive sensing. Each sensing cell consists of a transparent capacitor electrode (ITO), connected to two transparent TFTs. In microscopic scale, the surface of the fingerprint may have deep part like a valley or elevated part like a ridge. When the ridge of a fingerprint lies directly over the electrode, a capacitor is formed between the electrode and the finger. The capacitor between the sensor plate and the finger surface is charged by switching on the transparent charging transistor with the discharging transistor kept off, and then switching off the charging transistor. The saved charges depend on the distance between the sensor plate and the finger surface. If a valley in the fingerprint lies over the electrode, then the capacitance is much smaller, and a negligible charge is saved. The stored charge is later transferred onto a data line electrode by switching on the discharging transistor when the next column is activated. The charge is then amplified by a charge amplifier and processed by an external readout circuit.

An abstract model that demonstrates the capacitance difference between ridge and valley is shown in Figure 4. Based on the model, the sensor capacitance is at its maximum value when a ridge has contact with the capacitor electrode. As the distance between the chip surface and the fingers skin increases, the capacitance becomes smaller. By recognizing these variations on capacitance value, the valley and ridge of fingerprint pattern can be constructed. The same principle is also applicable to touched versus untouched area by a finger. The capacitance according to the distance is shown in Figure 5. The data is obtained from COMSOL Multiphysics simulation where we used a detailed model of the sensor cells

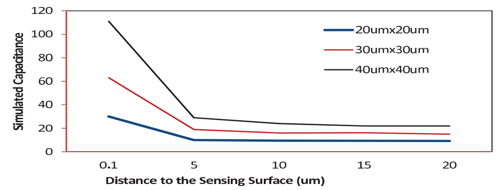


Fig. 5. Capacitance between finger to sensing surface. Simulation result from Comsol Multiphysics.

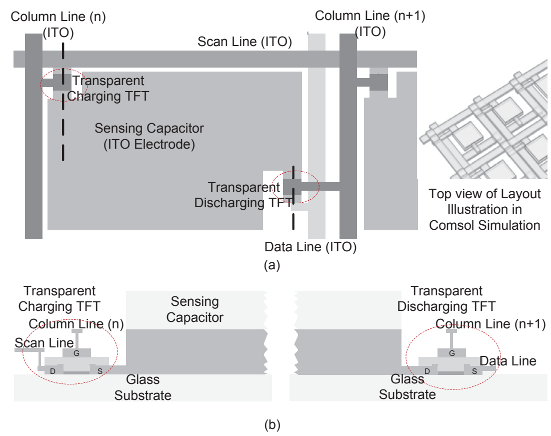


Fig. 6. Layout of capacitive sensing cell. (a) Plane view illustrating capacitor electrode, charging and discharging TTFT. (b) Schematic view of the cross sections. Proportions of different components are not based on actual sizes.

with ITO capacitor electrode.

Generally, the fingerprint pattern has line width and space in the range of 200 μm to 400 μm. To achieve a reasonable resolution for an acquired fingerprint image, the size of unit sensor cell should be around 60 μm x 60 μm. For illustration, Figure 6 shows example layout of the capacitive sensing array. Each sensing cell contains two TTFTs, one used as a charging switch and the other one used as a discharging switch. The TTFT is 400nm thick.

III. Implementation and Simulation Results

A. Readout Circuits and Dual Operation Modes

Figure 7 is a schematic block diagram of the touch-fingerprint sensing system. The system comprises of a capacitive sensor array that consists of many sensor cells for detecting the capacitances and can be used for both touch detection and fingerprint scan, row and column driving circuits for sequentially charging and discharging the sensing cells in rows and columns, and signal processing circuit. The signal processing circuit amplifies the sensed signal, converts the analog ridge/valley output into digital data, and stores them in latches. The capacitive sensor and the readout circuit can be connected by wire bonding or integrated together using system on-panel technique.

b) TFT Driver Circuits: The row shift register is for vertical direction scanning. A scan line becomes high voltage if it is selected. So the scan lines are utilized mainly for voltage supply lines to the sensing cells. For supporting high performance dual mode operations (touch sensing and fingerprint scan), the column driving circuit comprises multiple column shift registers for scanning in horizontal direction.

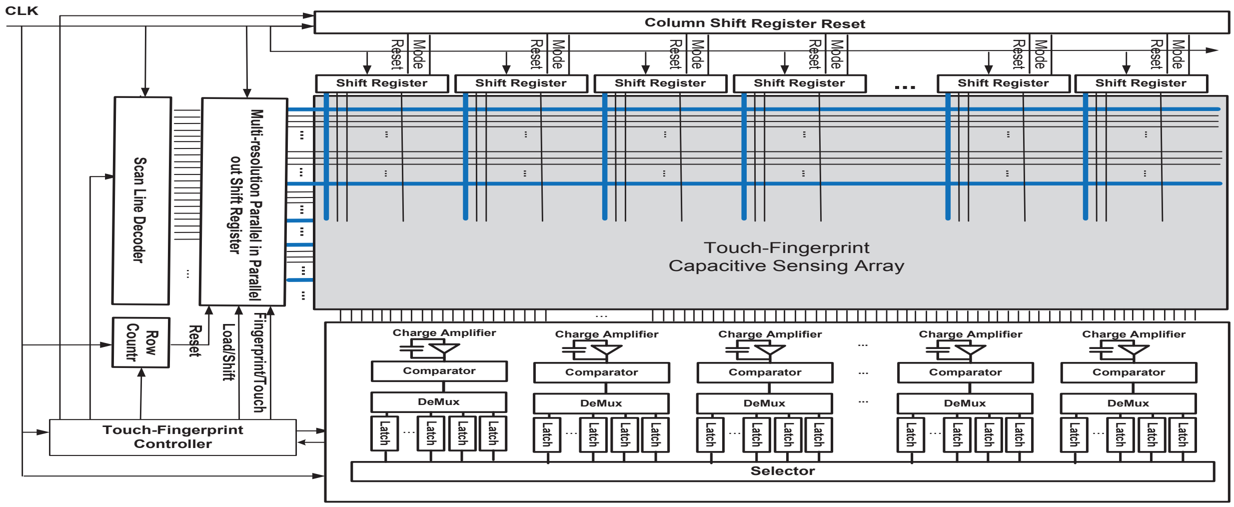
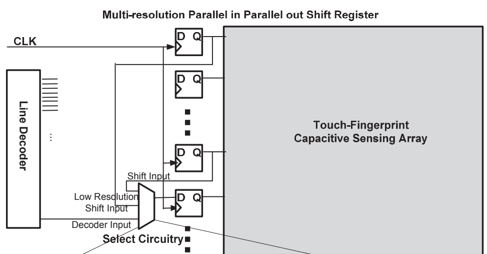


Fig. 7. Block diagram of unified TTFT touch-fingerprint system including optically transparent capacitive sensor array and non-transparent readout circuits. The row and column drivers support different sensor cell sampling resolutions for touch detection and fingerprint scan. Scanlines and columns in blue color are these activated in touch detection. The row driver can select the rows surrounding a touch location using a decoded start row address and a row counter.



Load	Shift	Fingerprint	Touch	Select
True	X	X	X	Decoder Input
X	True	True	X	Shift Input
X	True	X	True	Low Resolution Shift Input

Fig. 8. Multi-resolution shift register for supporting sub-sampling of scan lines.

Each column shift register connects to multiple column lines and selects them in a sequence. The sensing capacitor of a sensing cell in column X is first charged when its row and column are activated. Then when the next column X+1 is selected, the sensing capacitor will be discharged, and the sensing capacitor in column X+1 will be charged. The sensing array outputs the signals from the cells to the connected data lines. Columns connecting with different column shift registers can be charged and discharged in parallel. As shown in the figure, each group of columns has its own readout signal processing circuit.

Amplifier is used to transform the sensed voltage into current. After amplification, the outputs can be converted into digital signals using an A/D converter. In our current design, the outputs go through parallel analog comparators. The comparator compares the input potential with a reference potential to judge the touching surface and convert them into digital values. Such a design decision is made for achieving faster scanning speed and saving the cost of external controller because the readout circuit outputs digital signals and thus expensive high performance A/D converter is not necessary in the external controller. Since nearby columns are charged and discharged sequentially, the amount of cross-talk is reduced for fingerprint scan. Meanwhile, columns of different groups can be activated in parallel.

c) Multi-resolution Capacitive Sensing: A unique novel aspect of our capacitive sensing system is that it supports dual operation modes for both touch sensing and fingerprint scan. This is achieved using multi-resolution row and column drivers that support high resolution sampling of sensor cells for fingerprint scan, and low resolution sensor cell sampling for touch detection. The row driver consists of a multi-resolution shift register such as that shown in Figure 8. A row decoder can decode a given row address and store the decoded line in the shift register. In shift mode, the shift register can select rows sequentially with different row stride distances depending on whether the system is set to detect touches or scan fingerprints. For fingerprint scan, the rows will be selected one after the other with the maximum resolution. For touch detection, the rows will be selected with reduced resolution. For example, in touch detection, the row driver can select every 8th rows.

For column selection, dual operation modes for fingerprint and touch sensing are supported by splitting columns into multiple independent groups. Each group has its own shift register. For touch detection, one column from each group will be selected. The shift register doesn't sweep through all the columns. For each group, only the selected column will be charged and discharged. For fingerprint scan, the columns in each group will be charged and discharged sequentially. Different columns can share the same comparator. Each column has its own latch for storing the binary output after comparison. For each group, a DeMUX is used to select which latch should receive the converted digital output of a column.

For touch detection, the sensing system outputs a NxM pattern image with reduced resolution. By subjecting the pattern image to image processing, the touch location can be determined. For fingerprint scan, sensing cells will be sampled at the maximum resolution. However, not all the rows and columns are needed for fingerprint scan. For efficient and fast fingerprint scan, the sensing system first determines the location of the finger using touch detection mode. Then when fingerprint scan is needed, the sensing system only selects the rows and columns surrounding a finger touch location. This is achieved by sending a row scan address to the row driver. For example, assume that in touch detection mode, a central touch

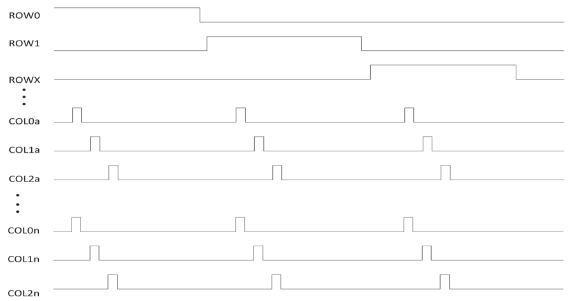


Fig. 9. Example sequences of row and column control signals. COL0a, COL1a, COL2a are in one column group. COL0n, COL1n, and COL2n are in another column group.

location is detected at row X. Then in fingerprint scan mode, the row driver can start selection of the rows from row X - d where d is determined based on the size of finger tip. There is a row counter that stores the number of rows that need to be scanned before it rotates to the beginning row, X-d. Similar design also applies to the columns. The sensing system can select columns outputs stored in the latches surrounding the touch location.

B. Output Characteristics of Simulation Results

We implemented the designed touch-fingerprint sensing system using Silvaco CAD tools. Simulation of the capacitive sensing array is carried out in SmartSpice and based on transparent TFT model module using Hoffman's closed form approach written in Verilog-A. Readout circuits are designed using conventional techniques such as CMOS or Polycrystalline Silicon (*e.g.*, [3], [4], [14]). The readout circuits don't need to be transparent. An optimization is to design the readout circuits with system on-panel techniques so that they can be integrated with the glass substrate, which is a subject of future work. Figure 9 shows example control signals for the readout circuits. Figure 10 shows the simulated output of the touch-fingerprint sensor for ridge and valley, the negative voltage value is the result of an inverting amplifier action. Table II lists the important parameters used in the circuit simulation. The driving circuits have a clock speed of 333.33KHz and supply voltage of 5V. The charging and discharging transistors are transparent SnO_2 TTFT with a turn on voltage of 2.7V. The channel mobility is 17.4cm$^2s^{-1}v^{-1}$. The capacitor electrodes, scanlines, column lines, and data lines are all made from ITO. For supporting touch-fingerprint dual sensing modes, the row driver uses multi-resolution shift register with shift stride distance of 1 or 8 corresponding to fingerprint and touch sensing respectively. The device consumes 1mW power, which is comparable with multi-touch panel of similar size.

The results indicate that output signals depend on whether cell capacitor electrode connects to a ridge or valley of the finger surface. After amplification, the output voltage difference between ridge and valley at maximum can reach 0.46V.

C. Applications

One potential application target of the unified capacitive touch-fingerprint panel is touch based handheld mobile devices. Such device supports both user mobile device interactions and novel identity management approaches such as continuous user identity management in the background when a mobile user interacts with a handheld device. For example, whenever a user tries to access a file by touching its icon, the user's identity can be verified first. According to the forecast, the size of identity and access management market will exceed $12 Billion in 2014. Mobile identity management is one of the rapidly growing sectors and driving forces because increasing number of employees from both government and private industry are using mobile devices to access confidential and proprietary information.

For broader impact, it may not be cost effective to create unified capacitive touch-fingerprint panels as large as a mobile screen. Such concern may not be a real issue given that multi-touch panel was considered an expensive technique before it became widely adopted. Like any other consumer electronic

TABLE II
SPECIFICATIONS OF THE CAPACITIVE TOUCH-FINGERPRINT SENSING SYSTEM

Touch-fingerprint capacitive sensing array	
Process	low temperature amorphous oxide semiconductors on glass substrate
Cell size	60 μm x 60 μm
Sensor array size	19.2mm x 53.7mm
Number of rows and columns	320 x 896
Row/column subsampling resolution	40 x 112
Frequency	333.33KHz
Supply voltage	5.0 V
Power consumption	1mW
Transparent TFT	
Mobility	17.4cm$^2s^{-1}v^{-1}$
Size	5 μm/5 μm (L/W)
Channel	SnO_2
Gate/source/drain	ITO
Turn-on voltage	2.7V
Speed	
Touch sensing	0.6ms
Fingerprint sensing	8.25ms

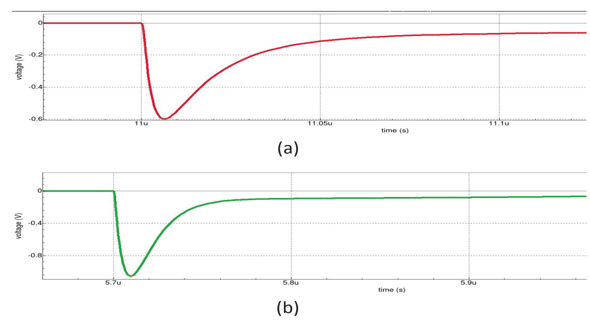


Fig. 10. Simulated output between ridge and valley after amplification (Vdd = 5V, Freq=333.33Khz). (a) Output induced by valley after amplification. (b) Output induced by ridge after amplification.

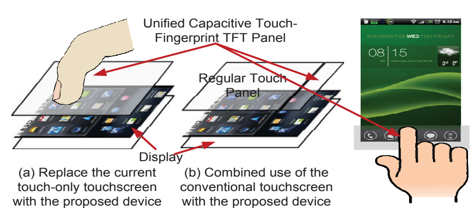


Fig. 11. Illustration of mobile devices with unified touch-fingerprint panel. (a) Replacing the existing touchscreen with our touch-fingerprint device for a broad range of protection. (b) A smaller touch-fingerprint panel can be used in conjunction with a conventional touch panel. Important user interface items (*e.g.*, unlock button, start button) can be displayed behind the touch-fingerprint panel. The system first detects user touches, determines touch location, and then scans fingerprint for identity recognition before responding to the touch.

techniques, mass production will drive down the cost. As a lower cost alternative, a mobile device can have part of its screen covered by a touch-fingerprint panel, see Figure 11 as an example. A mobile operating system can display important user interface items (*e.g.*, home button, start button, unlock button) behind the smaller touch-fingerprint panel. When the mobile device is locked, an unlock button will appear over the fingerprint sensor. A user has to touch the unlock button before unlocking the mobile device. Therefore, only registered users with known identity are allowed to unlock the device. Vendors can gain a competitive edge by adopting the designed technique and providing features such as anti-theft and user friendly identity control. Governments and enterprises are the most likely early customers.

IV. Related Work

The related work can be categorized into three groups, fingerprint sensing, capacitive touch panels, and smart mobile devices integrated with standalone fingerprint sensors. Different fingerprint sensing techniques have been studied in the past, including optical sensing, capacitive sensing, membrane, and thermal. In [13], the authors describe a capacitive fingerprint circuit by using CMOS process. Authors in [4], [3] fabricated a fingerprint sensor circuit by using low-temperature Poly-Si TFTs. However, none of these proposed fingerprint sensors are optically transparent and support integration with a display using a stacked structure. Furthermore, none of them support dual usage of the device as a fingerprint sensing device and a standard multi-touch panel. Due to the popularity of touch based mobile devices, there is a growing body of literature on capacitive touch panel (e.g., [7], [10]). However, the main differences between our work and the prior art in multi-touch panel are, our solution unifies capacitive sensing based multi-touch panel and fingerprint scanner into one device using transparent oxide electronics, and supports both touch screen mode and fingerprint scan mode with a novel multi-resolution driver design. The existing research only deals with touch panel design at low sensing resolution for detecting touch locations. Our solution provides a multi-resolution sensing mechanism that supports both fingerprint scan and touch detection with a unified driver circuit. Our design is the first of its kind with both capabilities in one device and supports integration with a conventional display. The demand for better security protection on smart mobile devices motivated device makers to integrate smartphones with standalone fingerprint sensors (e.g., Motorola Atrix 4G and iPhone 5S). Figure 12 shows some of the main differences between usage of our device and standalone, non-transparent fingerprint sensors. In [2], the authors present a design where transparent fingerprint sensors are overlayed on top of a conventional touch panel for identity management. However, the fingerprint sensor in [2] cannot operate as a multi-touch sensing device. Our paper first time describes a unified sensing system that can act both as a touch panel and fingerprint scanner. Our approach provides the flexibility to be integrated directly with a mobile display, as a result, user identity can be verified during normal touch interaction between a user and a mobile device.

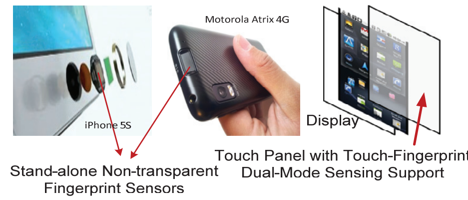


Fig. 12. Comparison of mobile devices with stand-alone fingerprint readers versus mobile devices using touch panel with dual mode support for touch sensing and fingerprint sensing. One main advantage brought by unified touch-fingerprint sensing device is enabling of mobile authentication during natural human-mobile device interaction. Non-transparent, stand-alone fingerprint sensors don't provide the flexibility to be used in combination with a mobile display and to support burdenless mobile authentication with minimal disruption to rich mobile interaction experiences.

V. Conclusions

This paper explores a novel design and approach of an integrated device for touch interactions and fingerprint biometrics based identity management. The novel design is based on the advances of transparent oxide semiconductors, and the observation that touch panel and fingerprint scanner can be both based on capacitive sensing. We use higher resolution array for fingerprint scanning while lower resolution for touch interactions. Our experiment shows that the fingerprint sensing is quick and power efficient, which demonstrates that this touch-fingerprint sensing panel can meet the requirements of two crucial functionalities that is yet to see it's light in the market.

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